Comparison of Soil Moisture Retrieval Algorithms Using Simulated HYDROS Brightness Temperatures

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***Abstract*—The HYDROS mission objective is to collect global scale measurements of the Earth's soil moisture and land surface freeze/thaw conditions, using a combined L band radiometer and radar system operating at 1.41 and 1.26 GHz, respectively. In order to examine how HYDROS soil moisture retrieval will be performed and how the retrieval accuracy will be impacted by vegetation water content and surface heterogeneity, an observing system simulation experiment (OSSE) was conducted using a modeled geophysical domain in the south-central United States centered on the Arkansas-Red River basin for a one-month period in 1994. Three separate radiometer retrieval algorithms were evaluated: (1) a single-channel algorithm (H polarization), (2) a two-channel iterative algorithm, and (3) a two-channel reflectivity ratio algorithm. Analysis indicates that the HYDROS accuracy goal of 4% volumetric soil moisture can be met anywhere in the test basin except woodland areas. Nonlinear scaling of higher resolution ancillary vegetation data can adversely affect algorithm retrieval accuracies, especially in heavy tree areas on the east side of the basin.**

Keywords - soil moisture, HYDROS, retrieval algorithms, microwave radiometry

I. INTRODUCTION

The Hydrosphere State Mission (HYDROS) has been selected by NASA for a flight opportunity under its Earth System Science Pathfinder program, with launch currently scheduled for 2010. The HYDROS mission objective is to collect global scale measurements of the Earth's soil moisture and land surface freeze/thaw conditions, using a combined L band radiometer and radar system operating at 1.41 and 1.26 GHz, respectively [1]. Data from the radiometer alone will permit retrieval of soil moisture in diverse (non-forested) landscapes with a spatial resolution of 40 km, while soil moisture products at 10 km will be generated in combination with higher-resolution radar data. An important issue in development of a dedicated spaceborne soil moisture sensor has been concern over the reliability of soil moisture retrievals in more heavily vegetated areas and the global extent over which accurate information can be obtained. In order to examine how HYDROS soil moisture retrieval will be performed and how the retrieval accuracy will be impacted by vegetation water content and surface heterogeneity (variability of land cover type and biomass), an observing system simulation experiment (OSSE) was conducted using a modeled geophysical domain in the south-central United States centered on the 575,000 km^2 Arkansas-Red River basin for a one-month period from May 26-June 28, 1994 (Figs. 1, 2). A land surface model was used to generate realistic geophysical parameters for the test basin at a 1 km scale, incorporating a diversity of vegetation and land cover types with representative dynamic ranges of soil moisture, temperature, and other surface characteristics [2]. Radiometer brightness temperature and radar backscatter values were then computed at the HYDROS frequencies, polarizations, and 40° incidence angle at the 1 km scale using a forward microwave emission and backscatter model, expected instrument noise was added, and results were aggregated to approximate the HYDROS instrument resolutions of 40 km for the radiometer and 3 km for the radar. Various retrieval algorithms were applied to these simulated HYDROS measurements, and the retrieved soil moistures were compared with the original soil moisture 'truth' fields (after degrading these to the approximate sensor resolution) to obtain error characteristics. The OSSE was repeated for special cases of doubling and tripling the vegetation in the test basin to insure a fair test of retrieval algorithm performance under high vegetation water conditions.

In this paper only the OSSE radiometer results will be discussed. Three separate radiometer soil moisture retrieval algorithms were evaluated: (1) a widely-used single-channel algorithm (H polarization), (2) a two-channel iterative algorithm currently used by AMSR, and (3) a new two-channel reflectivity ratio algorithm.

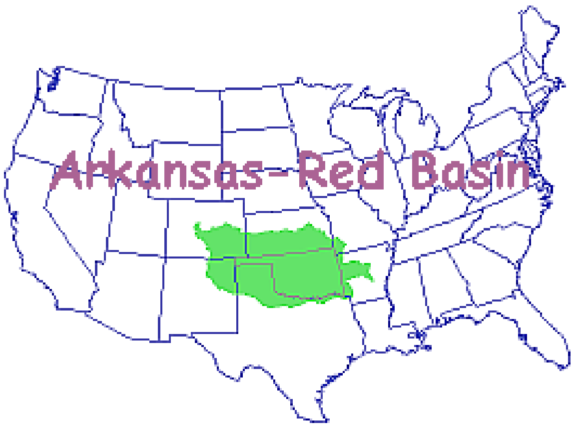

Figure 1. OSSE test domain in the Arkansas-Red River watershed.

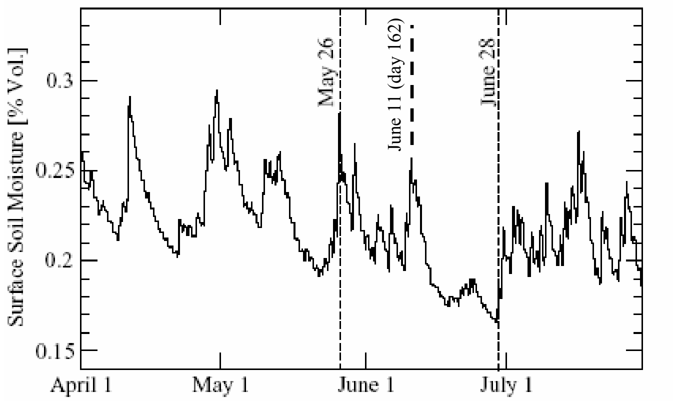

Figure 2. OSSE one-month test period in 1994.

II. MICROWAVE EMISSION

The L band modeled brightness temperature T_{Bp} includes components from the soil and vegetation and is expressed as

$$T_{Bp} = T_s\, e_p \exp(-\tau_p \sec\theta) + T_c\,(1-\omega_p)\,[1-\exp(-\tau_p \sec\theta)]\,[1 + r_p \exp(-\tau_p \sec\theta)] \qquad (1)$$

The subscript p refers to polarization (v or h), T_s is the soil effective temperature, T_c is the vegetation temperature, τ_p is the nadir vegetation opacity, ω_p is the vegetation single scattering albedo, and r_p is the soil reflectivity. The reflectivity is related to the emissivity by $e_p = (1 - r_p)$, and ω_p, r_p and e_p are values at the HYDROS look angle of θ=40°. Equation (1) assumes that vegetation multiple scattering and reflection at the vegetation-air interface are negligible at L band.

For the OSSE, the following assumptions were made. The unpolarized nadir vegetation opacity is related to the columnar vegetation water content W (kg/m^2) by $\tau_o = b\,W$ where the coefficient b depends on vegetation type [3]. The vegetation water content W is the average value over the 1-km pixel; no attempt was made to model fractional vegetation cover within a 1-km pixel. Surface roughness effects were approximated as $r_p = r_{sp} \exp(-h)$ where the parameter h is related to the RMS surface height s, and r_{sp} is the reflectivity of the equivalent smooth soil surface, determined by the soil dielectric constant ε using the Fresnel equations. For vegetated surfaces the vegetation temperature T_c was assumed to be equal to the soil surface skin temperature T_0. The soil microwave effective temperature T_s was estimated as the average of the surface skin temperature and the 5-cm temperature T_5. Since it was assumed that the effective temperature can be estimated from surface meteorological ancillary data (for simulated 6 am HYDROS overpasses) to within an accuracy of 1.5 K RMS, the computed and aggregated T_s data fields were perturbed with 1.5 K Gaussian random noise.

The canopy vegetation water content W_c was obtained from NDVI data using the relationship found in [4]. Since NDVI is sensitive to vegetation greenness, its signal comes primarily from the foliar canopy and not the woody components of the vegetation. In contrast, microwave signals include contributions from the water content of the trunks and branches as well as the leaves. Hence, for the OSSE simulations, a woody component fraction f_T was used to scale the foliar water content to a total vegetation water content W, where $W = W_c / (1 - f_T)$. The values assumed for the h, ω, b, and f_T parameters for each vegetation class can be found in Table II of [5].

To simulate HYDROS instrument error, spatially independent Gaussian noise with a standard deviation of 1 K was added to the 36-km brightness temperature retrievals. This was done independently for both radiometer polarizations and for each day of the simulation.

III. RETRIEVAL ALGORITHMS

During the OSSE three separate radiometer retrieval algorithms were evaluated which differ in their requirements for ancillary data:

- **Single channel algorithm --** H-polarized brightness temperature is corrected sequentially for surface temperature, vegetation water content, and surface roughness using ancillary data to obtain the equivalent emissivity for bare smooth soil; soil moisture is then retrieved using the Fresnel equations and the Dobson dielectric model [6]. This approach has been used extensively in the SGP and SMEX large field campaigns.

- **Multi-polarization iterative algorithm --** soil moisture and vegetation water content estimates are adjusted iteratively in computations of TB_v and TB_h (using Equation 1 and the Dobson dielectric model) until the difference between computed and observed brightness temperatures is minimized in a least squares sense; both soil moisture and vegetation water content are retrieved by this algorithm. This approach is currently used for AMSR retrievals.

- **Reflectivity ratio** -- the ratio of vertical to horizontal reflectivity (which is insensitive to vegetation and roughness) is derived from H- and V-polarized brightness temperatures using ancillary surface temperature data; soil moisture is then retrieved from this ratio using the Fresnel equations and the Dobson dielectric model.

IV. RESULTS

Figure 3 shows the root mean square error (RMSE) values for the retrieval algorithms for each day of the simulation for the baseline 1x W case across the entire test basin. Overall,

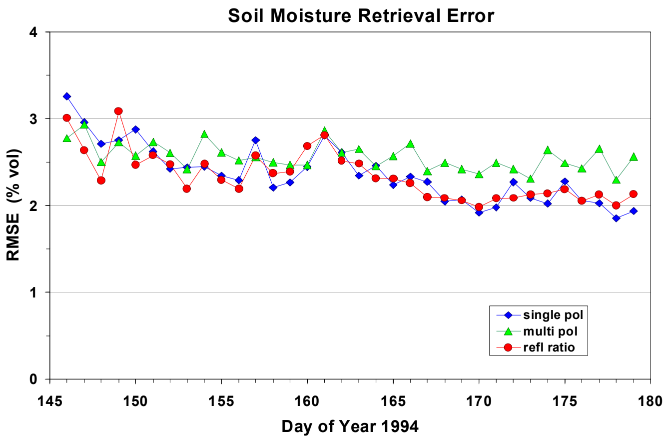

Figure 3. Basin average soil moisture retrieval accuracy (1x W case).

RMSE results for all three retrievals fall within the 1.5 to 3.5 % volumetric range, with the single polarization approach having a slightly lower RMSE. Despite the presence of significant temporal variability in soil moisture conditions within the basin (see Fig. 2), little temporal variability is observed in soil moisture retrieval error statistics. Although basin average retrieved soil moisture is accurate to better than 3.5% in all cases, the errors for individual 36-km pixels can be much larger, as seen in Fig. 4, in which soil moisture is plotted for each pixel in the basin for June 11 (day of year 162) for both the baseline 1x W and the artificially enhanced 3x W cases. Spatial patterns in retrieval errors appear to be driven primarily by the distribution of vegetation within the OSSE domain. All of the pixels in Fig. 4 with very large retrieval errors are found in the eastern 20% of the watershed where over 80% of the land cover is in tree, mixed woodland, or mixed woodland/crop/tree categories.

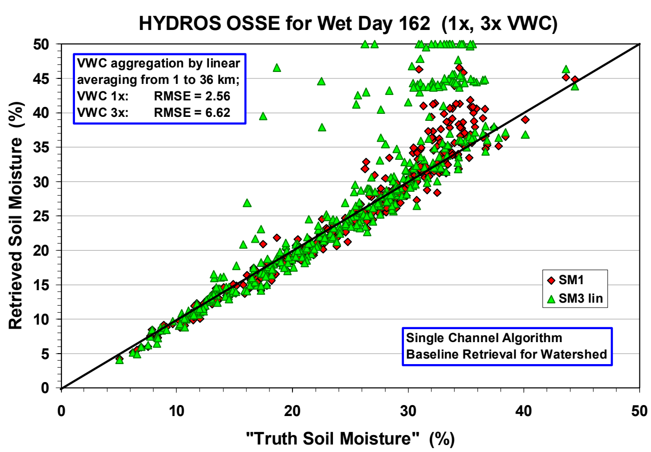

Figure 4. 36-km pixel scale soil moisture for June 11 (1x, 3x W cases).

The three retrieval algorithms tested differ in their ability to retrieve soil moisture accurately in the presence of larger W or woody vegetation. Figure 5 shows retrieved soil moisture RMSE (Figure 5a) and bias (Figure 5b) stratified by the mean vegetation water content (W) contained within each 36-km pixel. Despite relatively low errors for the watershed as a whole, significant errors are present in both the single and multi-pol approaches to soil moisture retrieval for the relatively small number of heavily vegetated 36-km pixels. A

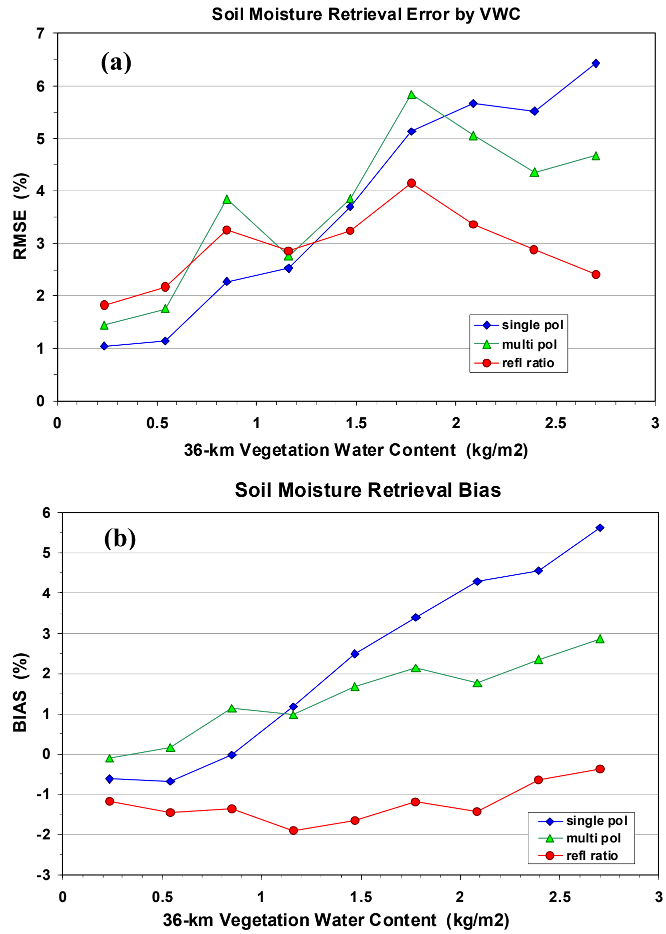

Figure 5. (a) RMSE and (b) bias stratified by vegetation water content.

large fraction of this error is associated with a positive bias in retrievals for heavily vegetated pixels, with the single channel algorithm having the largest bias and thus the worst accuracy. This is the only algorithm to rely on directly or linearly averaged W values to perform 36-km soil moisture retrievals, and it appears that the large bias with large 36-km W is related to nonlinear aggregation effects in scaling up the original 1-km W to 36-km W to match the HYDROS T_B scale. To test this possibility, the single channel algorithm was applied to the original data to retrieve soil moisture at 1 km, and the retrieved soil moisture was then aggregated to 36 km (previously the ancillary data were aggregated to 36 km first and then input into the single channel algorithm to retrieve 36-km soil moisture). Results, which are plotted in Fig. 6 for June 11 (compare to Fig. 4), indicate that use of the original non-aggregated W and other parameters at the 1 km scale greatly reduces the bias in soil moisture retrieval at large W and produces very accurate retrievals even for the 3x W case. Similarly, Fig. 7 compares the bias results for the 3x W case obtained using the baseline approach of 36-km aggregated data (lin VWC curve) against the improved results of retrieving soil moisture at 1 km and then aggregating to 36 km (SM 1 km curve). The third curve in Fig. 7 (eff VWC) is a test of whether retrievals improve at large W by using an "effective" aggregated vegetation water content (derived in this case from the multi-pol iterative algorithm which is allowed to solve for effective 36-km W values based on

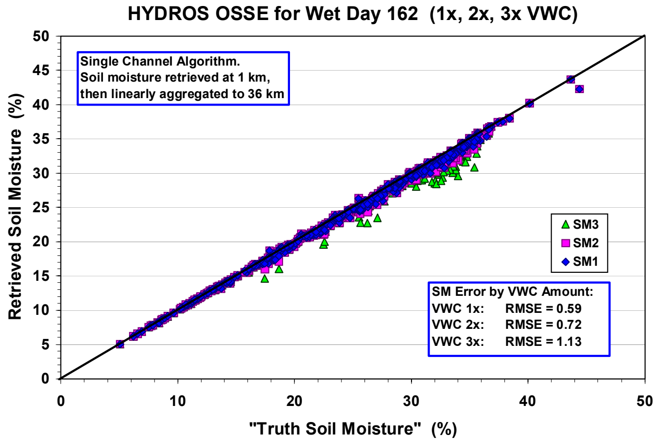

Figure 6. Single channel algorithm applied at 1 km , then averaged to 36 km.

optimal fitting to 36-km T_{Bh} and T_{Bv} observations and which generates 36-km W values for pixels with high W variability that are consistently biased low relative to those derived from direct aggregation of 1-km W fields). The use of such effective values appears to offer at least a partial correction to biases arising from aggregation impacts.

V. CONCLUSIONS

OSSE results indicate that the HYDROS accuracy goal of 4% retrieved volumetric soil moisture can be met anywhere in the test basin except woodland areas on the east side of the basin. Estimation of the correct vegetation parameters to use in the presence of woody vegetation requires further refinement and should result in improved algorithm performance in these areas. In addition, nonlinear scaling of higher resolution ancillary vegetation data to satellite footprint resolutions can adversely affect algorithm retrieval accuracies. Methods for "effectively" aggregating high resolution vegetation data to improve soil moisture retrieval algorithms for satellite microwave missions are currently under study, and will have direct relevance to the eventual choice of a baseline soil moisture retrieval algorithm for such missions.

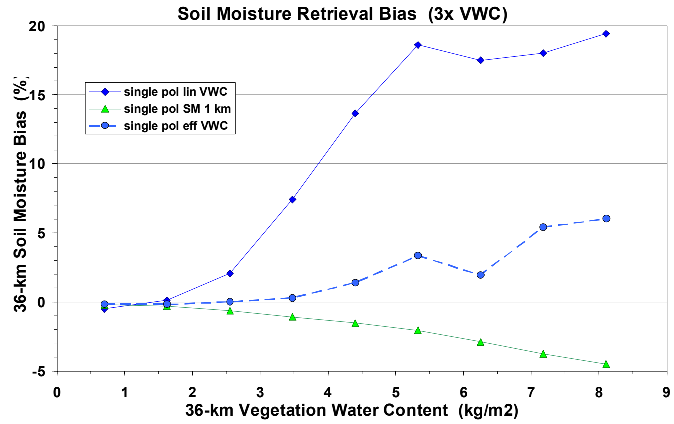

Figure 7. Single channel algorithm bias when applied using 36 km aggregated data (lin VWC), using original 1 km data (SM 1 km), and using an "effective" aggregation for vegetation water content at 36 km.

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